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A THEORETICAL STUDY OF THE PROPAGATION OF A MASS DETONATION

Philip M. Howe
Abdul R. Kiwan

February 1985

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The mass detonation problem was formulated as a dynamic probabilistic process, equivalent to a specialized bond problem in percolation theory. Percolation theory predicts that there exists a critical probability, above which there is a nonzero probability that an explosion will propagate throughout the munitions array. The critical probabilities for the generalized bond and site problems provide lower and upper bounds, respectively, for the critical probability for mass detonation.

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20. ABSTRACT (continued)

A Monte Carlo model was developed and exercised for two and three dimensional munitions arrays. The effects of synergy resulting from simultaneous detonation of nearest neighbors was examined, and anisotropies resulting from heightened or reduced propagation probabilities in one direction were addressed. It was shown that significant reductions in mass detonability can be obtained by exploiting anisotropic effects resulting from munition design.

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I. INTRODUCTION

A. Mass Detonability.

Ammunition items are assigned to various hazard classes, based on the level of risk considered acceptable for stipulated exposures. The maximum amount of explosives permitted at any location is determined by the prevailing distance from that location to other explosives. United Nations Organization (UNO) Class 1, Division 1 is composed of "mass detonating" ammunition and explosives. A "mass detonation" is defined as the "virtually instantaneous explosion of a mass of explosives when only a small portion is subjected to fire, severe concussion or impact, the impulse of an initiating agent, or to the effect of a considerable discharge of energy from without."[1] The majority of large caliber ammunition, e.g., 155 mm, 175 mm, 8" separate loading projectiles and general purpose bombs, are classified as mass detonating, and the constraints of mode of storage and transportation imposed to provide adequate safety create a significant economic and operational burden.[2] By use of appropriate packaging or shielding[3] or by use of different storage configurations,[4] the round-to-round propagation tendency can be reduced significantly with concommitant reduction in the tendency for mass detonation. The purpose of this effort was to determine, as a function of the munition array, how much the tendency for round-to-round propagation needs to be reduced to control explosion size and prevent mass detonation.

A Monte Carlo model was developed[5] and is exercised for two and three dimensional munition arrays. The effect of synergism resulting from simultaneous detonation of nearest neighbors is examined. The effects of anisotropics resulting from heightened or reduced propagation probabilities in one direction are also considered. It is shown that significant reductions in mass detonability can be obtained by exploiting the anisotropic effects resulting from munition design in their storage configuration.

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[1]*DARCOM Regulation 385-100, p 2-7 (17 Aug 81).*

[2]*"Safe Transport of Munitions," MTMC Report MTT81-1 (Jun 81).*

[3]*For example, M1 105 mm HOWITZER Ammunition is not mass detonating when packaged in its standard fashion, two to a box.*

[4]*P. Howe, "STROM Task 10 Report," in press.*

[5]*A. Kiwan, "A Monte Carlo Solution to the Problem of Survivability of Munitions Stores," ARBRL-TR-02163, Ballistic Research Laboratory, Aberdeen Proving Ground, MD (1979). (AD A071 459)*

B. Round to Round Propagation.

Numerous experiments have been performed with various types of ammunition to ascertain the nature of round to round propagation.[6-9] Of special interest to this effort, it was found that a straightforward criterion for round to round propagation could be developed; if a munition, in a regular array, subjected to the blast/fragment field of a detonating neighbor munition itself "detonated," then the blast/fragment field it generated could cause the next munition in the array to detonate, and propagation could continue within the array.[10] If, however, the munition subjected to the donor blast/fragment field reacted with subdetonation violence, the process would extinguish. No dependence upon the number of nearest neighbor munitions within the array was found; testing could be performed with a linear array (indeed, an array with one donor and one acceptor) and the results could be applied to two dimensional quadratic or hexagonal arrays. Apparently, the confinement provided by multiple nearest (second nearest, etc.) neighbors does not appreciably affect the ability of one munition to cause another munition to detonate. In the development of a model of propagation of detonation between munitions, one can thus apply a quantal response criterion, and treat the interaction probabilities between munitions pairs as independent.[11]

C. Model Development.

Consider a large, two dimensional array of munitions. (See Figure 1, showing a storage array for 155 mm separate loading projectiles. Here, the array is three dimensional, but little loss in generality occurs as a result of considering the two dimensional case.) Of interest is the size of the explosion (i.e., the number of participating munitions) resulting from the

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[6] *P. Howe, "The Response of Munitions to Impact," ARBRL-TR-02169, Ballistic Research Laboratory, Aberdeen Proving Ground, MD (1979). (AD B040 230L)*

[7] *G. Gibbons, "Multiple Round Fragmentation Hazards and Shielding," ARBRL-TR-02329, Ballistic Research Laboratory, Aberdeen Proving Ground, MD (1981) (AD B058 793)*

[8] *J. Thomas and P. Howe, "Effectiveness Testing for Antipropagation Shields Developed for M456 HEAT Tank Ammunition, "ARBRL-TR-02370, Ballistic Research Laboratory, Aberdeen Proving Ground, MD (1981). (AD A107 037)*

[9] *F. Porzel, et al, "Naval Explosives Safety Improvement Program (NESIP): Summary and Status," NSWC-TR-81-27, Naval Surface Weapons Center, Dahlgren, VA (1976).*

[10] *Detonation- the quotation marks are provided, because it is not absolutely clear that the target rounds need detonate according to a rigorous definition of a detonation. For test purposes, a "detonation" was considered to occur if the target munition reacted with design mode violence, as indicated by production of numerous high velocity, small fragments, consumption of all the explosive, and perforation of a 2.5 cm thick mild steel witness plate. We currently believe that this level of violence can be obtained from a constant volume explosion, followed by very rapid case rupture. The point of importance is that an unambiguous quantal response criterion for propagation can be established.*

[11] *In order to treat a particular situation, the "independent" condition will be relaxed later in this paper.*

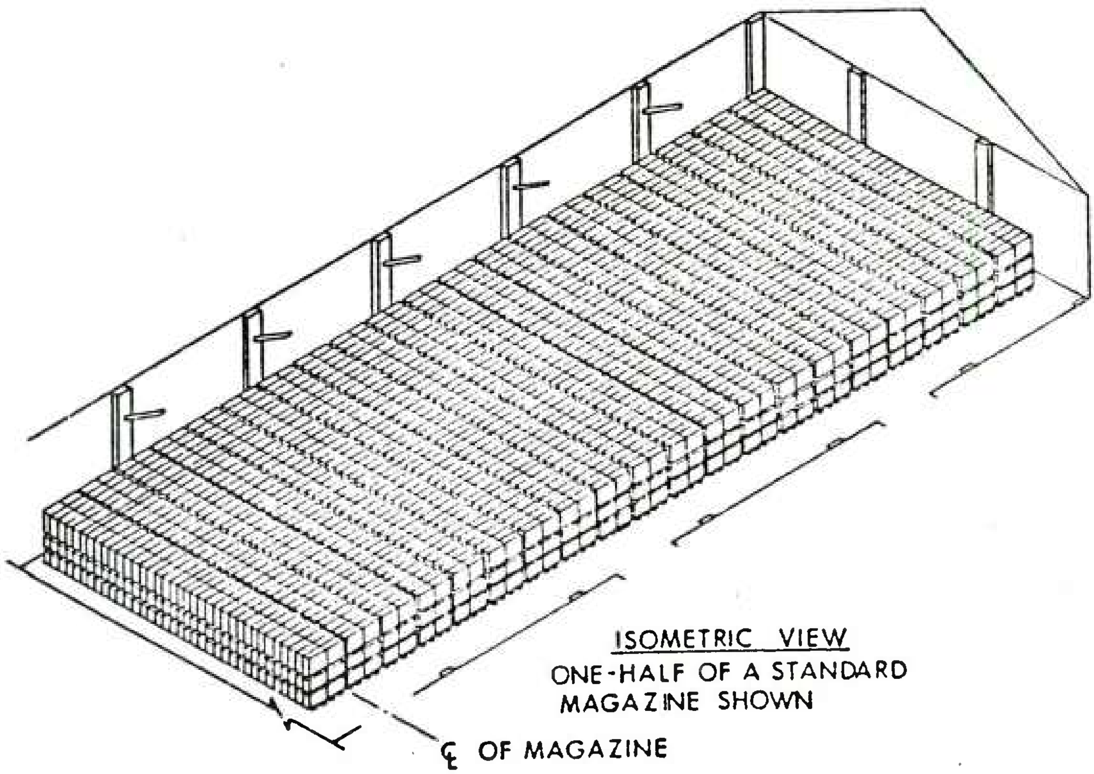

Figure 1. Storage array for 155 mm separate loading projectiles. Each box represents a pallet for 8 rounds.

detonation of a single munition. Since the munitions are nearly equidistant, the array can be represented by an infinite regular lattice, the vertices of which represent individual munitions sites. Because of translational symmetry, a chosen site is typical of the rest, and the origin can be chosen arbitrarily. Interest then centers upon the cluster of sites, containing the origin, and representing the number of munitions which participate in the explosion. Three assumptions are made:

1. Propagation of detonation occurs only through nearest neighbor interactions. Experimental evidence has been obtained in support of this. The nearest neighbor munitions effectively shield next nearest neighbors from direct fragment attack.

2. The interaction probabilities (i.e., the probability that one round will detonate another) are independent.

3. The process of propagation of detonation is Markovian. Only the last state of the process (whether or not set of rounds under considera- tion detonated) is relevant in determining whether or not the next set of

nearest neighbors will detonate. Experimental results generally support this assumption. However, in the limit of high packing densities, large munitions, thin munition walls, and deformation sensitive explosives, it is expected that this assumption would break down.

Let p be the interaction probability, i.e., the probability that detonation of one round will cause detonation of its nearest neighbor. Experimentally, p can be measured by observing results of a large number of repetitions of an experiment involving a donor and an acceptor round, separated by a spacing identical to that in the array of interest, and noting the fraction of acceptor rounds which "detonate," according to the criterion discussed in the introduction. Clearly, $q = 1 - p$ is the probability that the interaction is too weak to cause a round to detonate, given the detonation of the donor. In a quadratic lattice (for example), the donor or source has four nearest neighbors, which comprise members of the first generation. (By definiton, the source will be considered the zeroth generation.) The nearest neighbors of the munitions which detonated in the first generation comprise potential members of the second generation. The possible configurations for the zeroth through the first generation are shown in Figure 2. Note that the number of configurations for a given number of the first generation detonations is represented by the coefficients of the terms of the expansion:

$$(p + q)^4 = p^4 + 4p^3q + 6p^2q^2 + 4pq^3 + q^4.$$

The individual terms on the right hand side of this expression represent the probabilities of a given number of these neighbors being detonated. Denoting the expected or mean number of neighbors detonated by E(S) one has

$$E(S) = 4.p^4 + 3.(4p^3q) + 2.(6p^2q^2) + 1.(4pq^3) + 0.q^4$$

$$E(S) = 4p.$$

and $S(p) = 1 + E(s) = 1 + 4p$ and is the mean explosion size, including the donor.
This is to be expected because of assumption 2.

In Figures 2 and 3, the bonds indicate that a munition has detonated. In principle, this procedure of direct enumeration can be continued through r generations, where r is arbitrarily large. In practice, direct enumeration is difficult because of the extremely rapid growth in the total number of clusters. An additional complication arises in the situation of interest here, in that there is the physical constraint that we do not detonate the same round twice. In enumeration beyond the first generation, one must exclude forbidden configurations (see Figure 3). The means explosion size, S(p), is then equivalent to the mean number of bonds associated with clusters containing the source munition. Thus, in general, we can write

$$S(p) = \sum_{n=0}^{\infty} a_n p^n$$

where the infinite cluster is excluded.

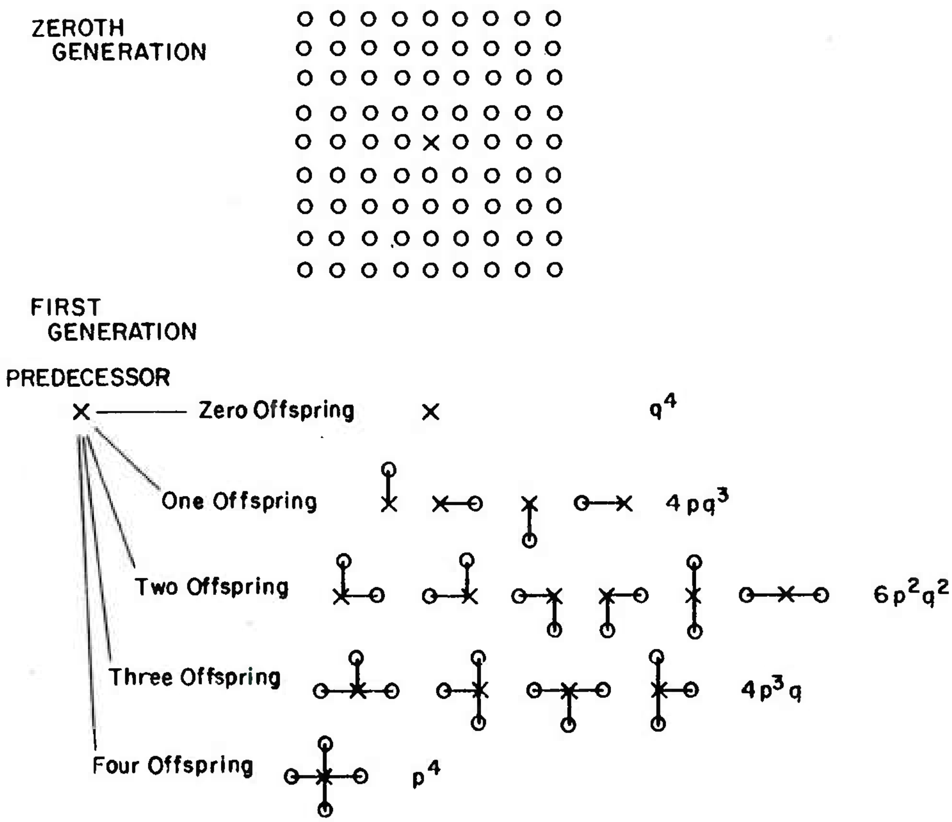

Figure 2. Simple quadratic lattice showing all possible configurations for clusters containing the source munition (x) and possible members of the first generation. The bonds indicate an interaction has occurred. Undetonated rounds are suppressed.

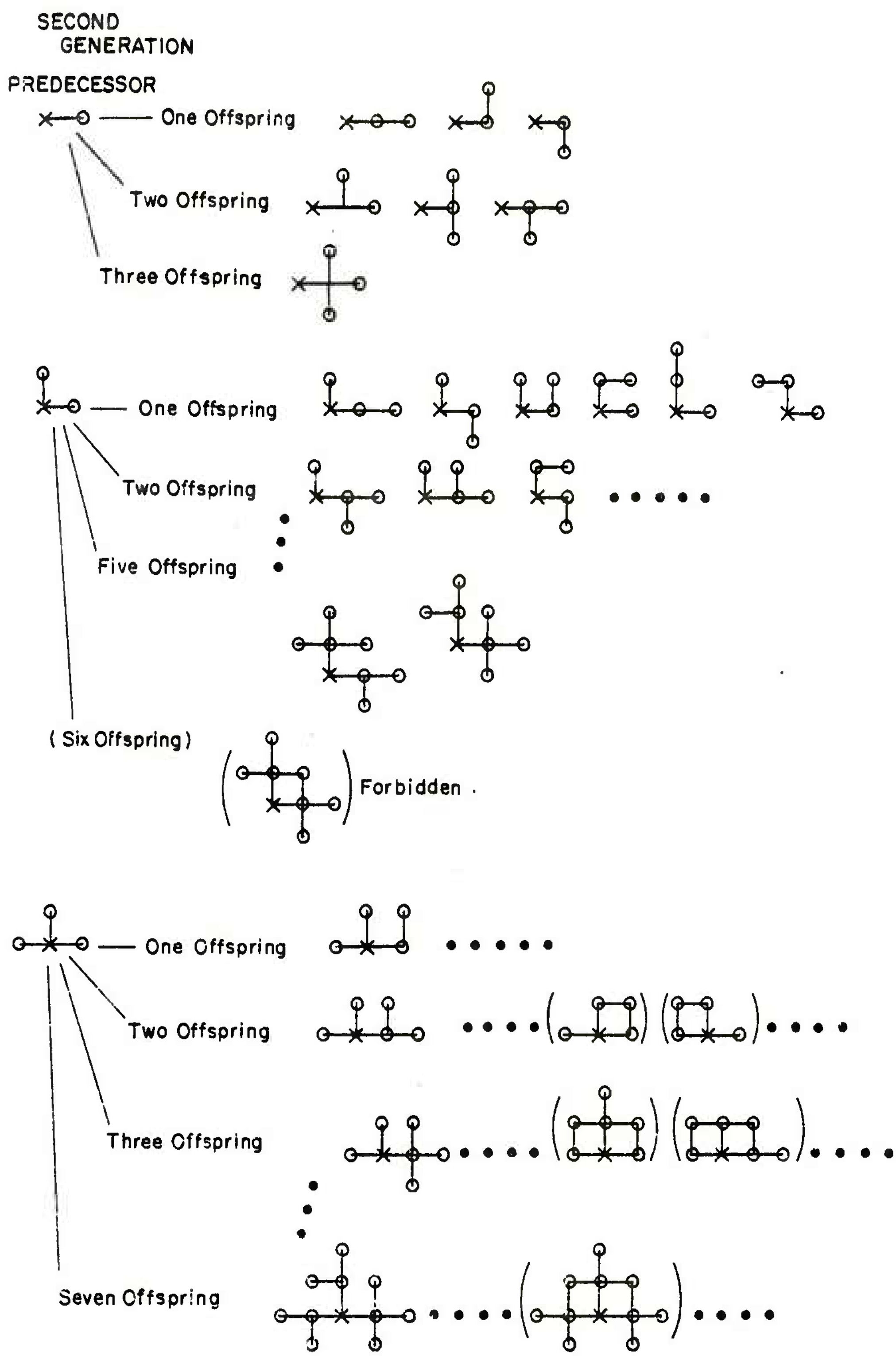

Figure 3. Some configurational members of the second generation. The configurations shown in parentheses are physcially unrealizable, as they correspond to situations where the same round is caused to detonate twice.

The description provided above of an explosion in a munitions array is a special case of a "bond" percolation problem.[12-13] It differs from the general case in that closed loops, as shown in Figure 3, are prohibited. Traditionally, the subject of percolation theory has been divided into two types of problems, the "bond" problem and the "site" problem.[14] In the bond problem, each pair of neighboring lattice sites has a probability p of being connected, independently of all other such pairs. In the site problem, each site has a probability p of being in state A and a probability q = 1 - p of being in state B. A site is contained within a multi-site cluster if there is at least one nearest neighbor in the same state. The site problem arises, for example, in models of binary alloys,[15] dilute ferromagnetic crystals,[16] and thermal conductivity of disordered two-phase materials.[17] The bond problem arises naturally in models of single phase dispersive flow of a liquid through a porous medium,[18] the propagation of a blight through an orchard,[19] or gelation of polymers.[20] The site problem is not a natural choice for modeling an explosion in stacked munitions, as the site probabilities are not easily measured experimentally while interaction probabilities (≡bond probabilities) are, at least in principle, directly measurable. However, it can be shown[21] that

$$P^{(s)}(n|p) \leq P^{(b)}(n|p),$$

where $P^{(s)}(n|p)$ refers to the probability of obtaining a cluster of size n, given an interaction probability, p, for the site problem, and $P^{(b)}(n|p)$ is

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[12] M. Sykes, M. Glen, "Percolation Processes in Two Dimensions I: Low Density Series Expansions," J. Phys. A: Math. Gen. 9, 87, (1976).

[13] A. Dunn, J. Essam, and D. Ritchie, "Series Expansion Study of the Pair Connectedness in Bond Percolation Models," J. Phys. C: Solid State Phys 8, 4219, (1975).

[14] For an excellent review of percolation theory, see J. Essam, "Percolation and Cluster Size" and C. Bomb and M. Green, Phase Transactions and Critical Phenomena 2, Academic Press, NY (1972).

[15] S. Broadbent and J. Hammersley, "Percolation Processes, I Crystals and Mazes," Proc. Cambridge Philosophical Soc. 53, 629 (1957).

[16] V. Shante and S. Kirkpatrick, "An Introduction to Percolation Theory," Adv. in Phys., 20, 325 (1971).

[17] Y. Yuge, "Three Dimensional Site Percolation Problem and Effective Medium Theory: A Computer Study," J. Stat. Phys., 16, 339 (1977).

[18] M. E. Fisher, "Critical Probabilities for Cluster Size and Percolation Problems," J. Math Phys., 2, 620 (1961).

[19] H. Todd, "A Note on Random Associations in a Square Point Lattice," Roy. Stat. Cos Supplement 7, 79, (1940).

[20] P. Flory, Principles of Polymer Chemistry, Cornell UP, Ithaca, NY (1953).

[21] J. Hammersley, J. Math Phys., 2, 728 (1961).

the probability of getting a cluster of size n for the bond problem. Since

$$S(p) = \sum_{n=0}^{\infty} n\, P(n|p),$$

$S^{(s)}(p) \leq S^{(b)}(p)$ and we can use the mean cluster size for the general site and bond problems, as lower and upper bounds, respectively, for the specialized bond problem of interest here. Vyssotsky, et al, have reported Monte Carlo estimates for the general bond problem in two and three dimensions for several lattices.[22] Frisch, et al, have reported similar estimates for the general site problem.[23] Plots of expected probability, p(n), of clusters of size n versus cluster size for their site and bond results are shown in Figure 4, for the simple cubic lattice.

For infinite lattices, a percolation probability, P(p), can be defined as the probability that an infinite number of sites will belong to the cluster containing the source. Thus,

$$P(p) = \lim_{n\to\infty} P_n(p),$$

where $P_n(p)$ is the probability of obtaining clusters at least of size n.

A critical probability, p_c, is defined as

$$p_c = \text{Supremum} \quad p|P(p) = 0.$$

For $p>p_c$, there exists a nonzero probability that there will be an infinite cluster, i.e., that the detonation will propagate to an infinitely large extent. For $p<p_c$, the mean explosion size remains bounded but grows exponentially as $p \to p_c$ and becomes infinite at p_c. Critical probabilities have been estimated for common lattices for site and bond problems by series expansion techniques and by Monte Carlo methods.[16] Some calculated values are shown in Table 1.

D. Monte Carlo Estimates.

The series expansion description described above provides useful information regarding mass detonation phenomena, but it does not have the flexibility required, to address readily, certain additional issues. For example, munitions rarely have isotropic interaction probabilities: design features are usually such that nose-nose or base-base interactions are enhanced or depressed vis a vis side-side interactions. Furthermore, experiments have shown that simultaneous or near simultaneous detonation of collocated munitions can generate an extremely lethal collimated blast/fragment field with high probability of detonation of munitions within its path. Thus, if a round causes two nearest neighbors to detonate simultaneously, the probability of detonation of the next nearest

[22] *V. Vyssotsky, et al, "Critical Percolation Probabilities (Bond Problem)," Phys. Review 123, 1566, (1961).*
[23] *H. Frisch, et al "Critical Percolation Probabilities (Site Problem)," Phys Review 124, 1021, (1961).*

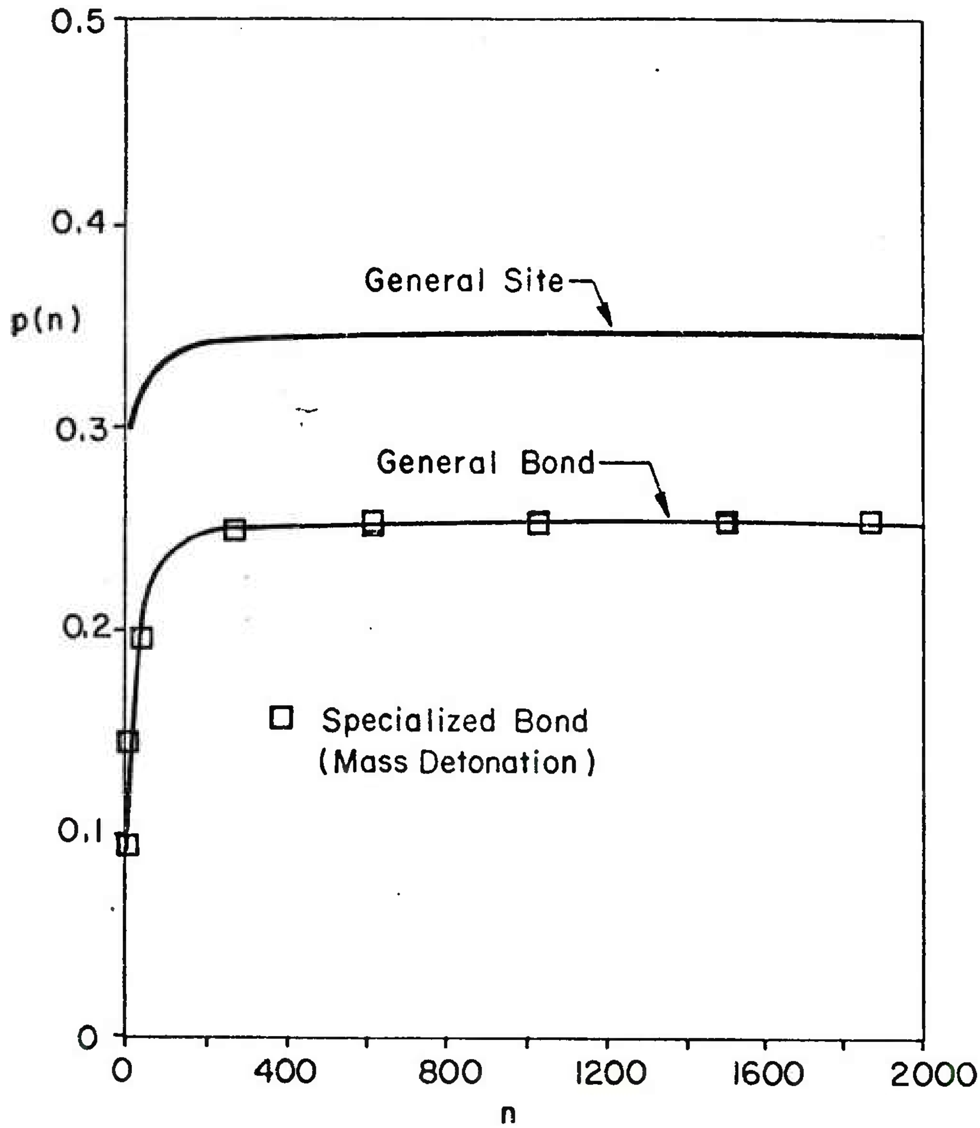


Figure 4. Expected probability of cluster size versus mean cluster size for general site and bond problems[22,23] and specialized bond problem for a quadratic lattice. Note that proscription of closed loops does not significantly change bond calculation results.

TABLE I

CRITICAL PROBABILITIES FOR COMMON LATTICES

Lattice	Monte Carlo $P_c(b)$	Monte Carlo $P_c(s)$	Series Method $P_c(b)$	Series Method $P_c(s)$
Honeycomb	0.640	0.688	0.6527 (exact)	0.700
Kagome	-	-	-	0.6527 (exact)
Square	0.493	0.581	0.5000 (exact)	0.590
Triangular	0.341	0.493	0.3473 (exact)	0.5000 (exact)
Diamond	0.390	0.436	0.388	0.425
Simple Cubic	0.254	0.325	0.247	0.307
Body Centered Cubic	-	-	0.178	0.243
Face Centered Cubic	0.125	0.199	0.119	0.195
Hexagonal Closest Packed	0.124	0.204	-	-

Ref. (16)

neighbor in common with these two munitions is essentially unity. To address these problems and others, a Monte Carlo model was developed.[5] This model is capable of handling both site and bond problems in one, two, and three dimensions. The computation is started by setting up the computational lattice as specified by the input. A site of the lattice, representing a munition round, is selected at random. The selected round is considered to be detonated. If the input specified that more than one round is initially detonated then a program subroutine is called to select the remaining rounds of the initial reaction set (ISET) from the nearest neighbors of the randomly selected site. An array (IND) in this computational model keeps record of the status of each round in the lattice. Thus, in a two dimensional bond problem, IND(i,j,1) = 1, if the reaction propagated to the round at (i,j,1), IND(i,j,1) = 0, otherwise. At the beginning of a typical cycle of calculations, the bonds emanating from all sites at the reaction front are examined to see which bonds block the reaction. This determination is achieved by using a random number generator to generate a continuous random number, r, such that $0 < r < 1$, and r has a uniform probability density distribution $f_r(r_o)$. The sample space for r is partitioned into two events;

(i) the event E_1, $(r < p)$, that the bond is unblocked and propagates the reaction to a neighboring round, and (ii) the event, E_2, $(r > p)$, that the bond is blocked and does not propagate the reaction to a neighbor. Because of the assumption that a round can only be initiated by an immediate neighbor, the search process is limited to the first generation neighbors of the reaction front. The newly detonated rounds form the reaction front for the next cycle of calculations. The location of the new reaction front at the end of each cycle is saved in coordinate arrays. The calculation cycles are terminated when no new rounds are detonated. This will complete a trial and a new trial is initiated up to an input specified number of trials, NTRIAL. At the end of each trial, the total number of reacted rounds in the reaction cluster for the trial is saved in an array, ND(j). At the end of the run, the mean reaction cluster size, and its standard deviation are computed and printed.

Several values of the interaction probability can be computed in a single run. The code has a number of options that can be either selected on input or achieved with a change of a few cards. The code will print out the hierarchy of the reaction branching process through the ammunition lattice if input specified. It is also possible to treat the nonisotropic case of unequal interaction probabilities p_x, p_y, and p_z. Another option treats the synergistic case of collimated blast/fragments, by making the interaction probability $p = 1$, when two neighboring rounds detonate simultaneously.

The mean explosion size, for a simple cubic lattice, as determined by our Monte Carlo calculations, is juxtaposed with the results of Vyssotsky, et al,

and Frisch, et al, in Figure 4. Our results are essentially identical to the results of Vyssotsky, et al, for the general bond problem. Evidently, restricting cluster configurations only to those which contain no closed loops has little effect upon calculated mean cluster size, or estimates of critical probabilities. Of special interest is the fact that the mean explosion size remains very small for $p < p_c$, and it is reasonable to take p_c as an upper bound of an acceptable interaction probability, with prevention of mass detonation the objective. As $p \to p_c$, mean explosion size grows very rapidly, approaching infinity at the critical point.

Shown in Figure 5 is the mean cluster size with and without the synergistic effect ("specialized bond") included, for the quadratic lattice. Note that the synergistic effect lowers somewhat the probability required to get an explosion of any given size, but does not radically change the results.

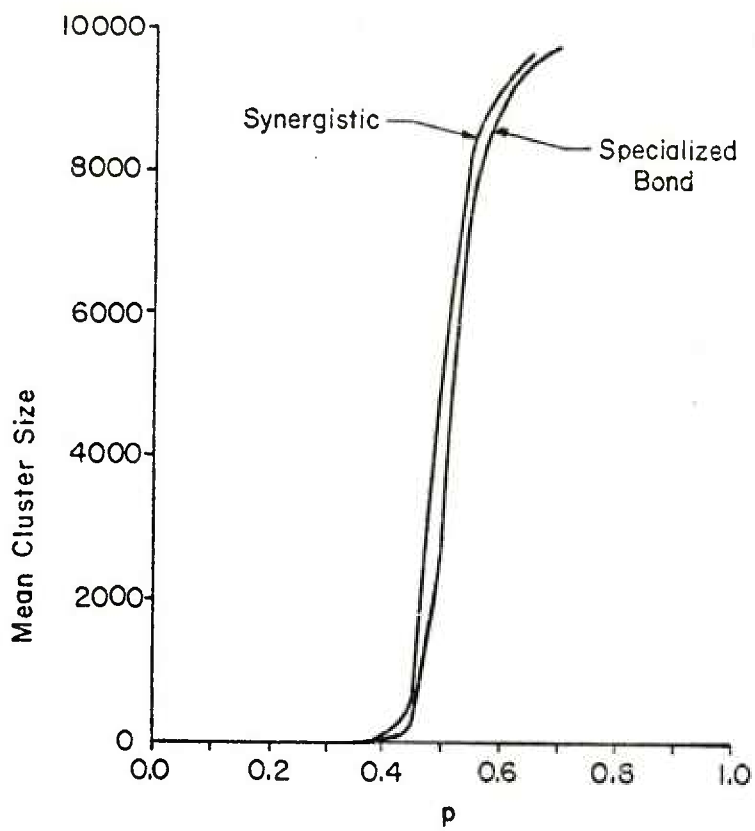
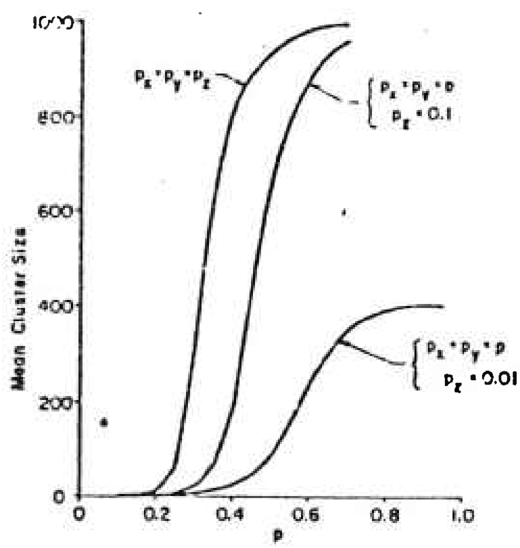


Figure 5. Mean explosion size for two dimensional square lattice, with and without synergistic effects.

In Figure 6, mean explosion size is plotted versus the interaction probability in the x and y directions, with P_z fixed at various values. Note that small values of P_z lead to greatly reduced explosion sizes. The roll-over at the top of each curve is due to edge effects caused by the finiteness of the 10 x 10 x 10 computational array. Not shown in Figure 6 is the curve for P_z fixed at unity. It would be to the left of the curve for $P_z = P_x = P_y$. Figure 7 shows calculations for the probability of getting an explosion of at least n rounds, as a function of P, in a 10 x 10 x 10 array for P_z unity and for P_z equal to a fixed fraction of p. As expected, the results of P_z equal to unity lie to the left of the results for P_z equal to a fraction of p. Holding P_z constant simulates fixing the munition design and spacing between rounds in the z direction. Letting P_z vary with P_x allows one to account for variation in explosive sensitivity, as well.



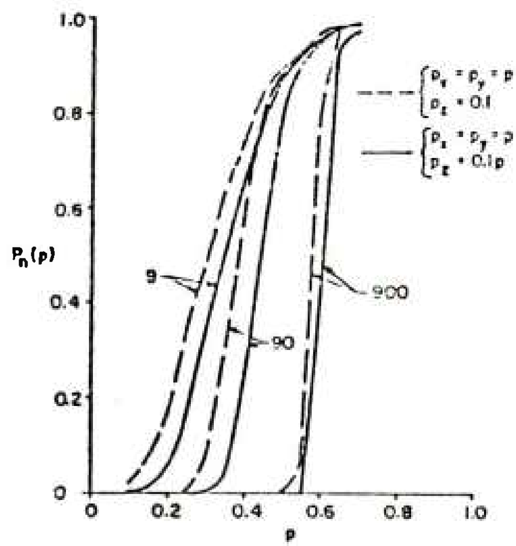


Figure 6. Mean explosion size versus interaction probability for simple cubic lattice: effects of anisotropy.

Figure 7. Probability of getting an explosion of at least n munitions, as a function of the interaction probability, for 3D cubic lattice: effects of anisotropy.

Very high values of P_z are representative of a shaped charge warhead detonation, where the formed jet represents a very severe threat to the opposite round in the next layer. Very low values of P_z are representative of artillery munitions, such as 155 mm and 8" shell, where the interaction probabilities between noses and bases are expected to be far weaker than the side-side interactions. The calculations show that this anisotropy can greatly reduce explosion size, for large three dimensional arrays. These calculations were used to design tests in which it was shown that explosion size could indeed be controlled by exploiting orientational effects. Thus, it was shown experimentally that 155 mm M107 shell (filled with TNT or composition B) will not propagate in base-base orientation when separated by as little as 25 cm, for pallet sized units. As unit size was increased above the standard 8 round pallet, larger spacings were required, but it was shown that explosion did not propagate between units as large as 8 pallets (64 rounds, with approximately 15 pounds explosive per round) oriented base to base, and nose to nose and separated by less than 60 cm (2 feet). It follows from these results that it is advantageous to store munitions in arrays such that the z-axis, with low interaction probabilities, is the long axis of the array. For transportation on rail, for example, artillery ammunition should be oriented nose-nose and base-base, with the munition axes parallel to the train axis, in order to minimize explosion size.

It might be expected that restricting the interaction probability to low values in one direction essentially reduces the three dimensional problem to the appropriate two dimensional problem. Thus, setting $P_z = 0.01$, for example, for arrays with simple cubic symmetry would produce results nearly equivalent to those for square arrays. In Figure 8, we show mean cluster size results for the simple cubic lattice, with $P_z = 0.01$, and results for the two dimensional square lattice. For small cluster sizes, the two problems are nearly equivalent. However, as the critical point is approached, the mean cluster size increases more rapidly for the three dimensional problem than for the two dimensional case. This is because propagaton in the z direction depends not only on P_z, but the number of sources, which depends on the size of clusters in the two dimensional arrays. Of considerable practical importance, it is noted that, as long as P_z is small, the same critical point criterion can be used for both two and three dimensional arrays.

II. SUMMARY AND CONCLUSIONS

The mass detonation problem has been formulated as a dynamic probabilistic process, equivalent to a specialized bond propagation problem in percolation theory. A Monte Carlo model was constructed, with the flexibility of treating both bond and site percolation problems, but subject to the constraint that no munition be allowed to detonate more than once. This constraint is equivalent to forbidding existence of closed loops in the cluster configurations. Calculations were made for two and three dimensional arrays.

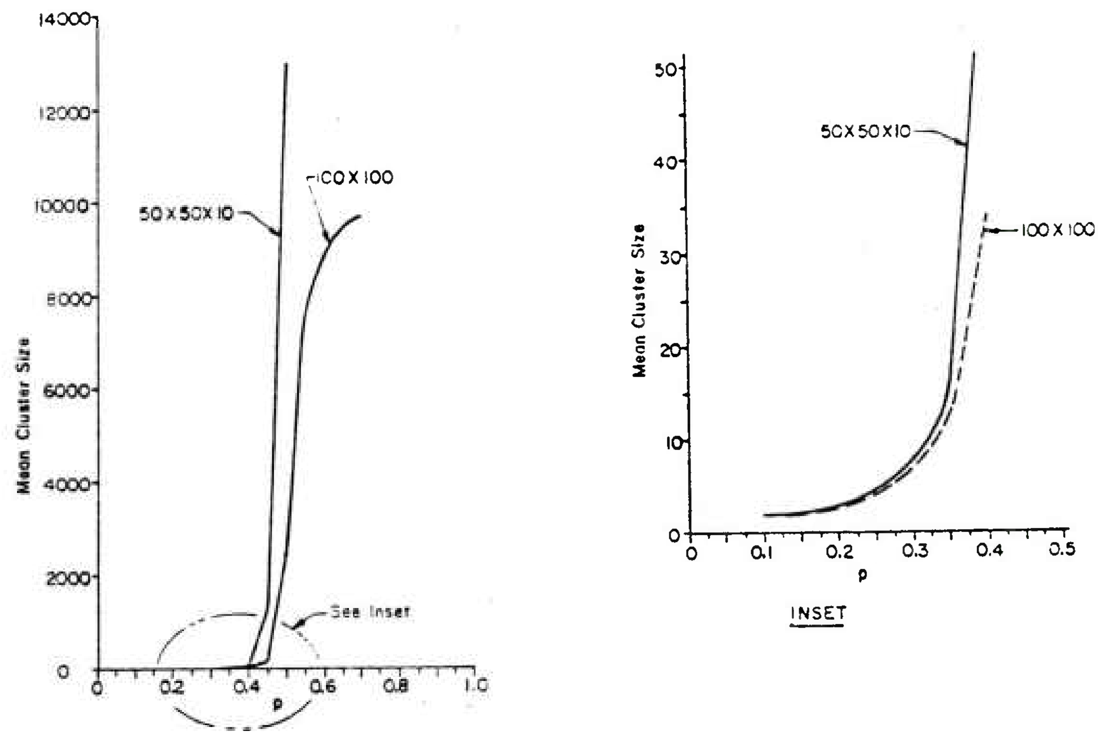


Figure 8. Comparison of results for square lattice and the simple cubic lattice, with $P_z = 0.01$. Note divergence of results at large cluster sizes.

Results of three dimensional calculations were compared with Monte Carlo calculations for the general site and bond problems as reported in the literature. The results of our specialized bond problem calculations are essentially indistinguishable from those for the general bond problem, indicating that the restriction of permissible configurations to trees has little influence on the results. Of special importance, it was found from plots of mean explosion size versus interaction probability that, as long as the interaction probability did not lie in the immediate neighborhood of the critical probability and to its right; the probability of achieving a mass detonation remains small. Thus, the critical interaction probability can be used to make estimates of the required munitions sensitivity to prevent mass detonation. The synergistic effect associated with simultaneous detonation of two rounds, causing near-unity probability of detonation of the next nearest neighbor, was treated and found to have a noticeable, but not strong effect on the mean explosion size and critical probability.

Anisotropic interaction probabilities can exert a very strong influence upon mean explosion size and probability of mass detonation. Thus, it was found that setting the interaction probability in the z direction to a high value - e.g., 0.8 -, as would be observed experimentally for stacked shaped charge warheads, led to very large explosion sizes, even for relatively low values of $p_x = p_y$. Alternatively, it was found that low values of p_z were very effective in limiting explosion size. This was verified experimentally using 155 mm projectiles, and it was found that there are significant reductions in mass detonability obtained by oriented artillery shell in nose-nose and base-base configurations.

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3. For example, M1 105 mm HOWITZER Ammunition is not mass detonating when packaged in its standard fashion, two to a box.

4. P. Howe, "STROM Task 10 Report," in press.

5. A. Kiwan, "A Monte Carlo Solution to the Problem of Survivability of Munitions Stores," ARBRL-TR-02163, Ballistic Research Laboratory, Aberdeen Proving Ground, MD (1979). (AD A071 459)

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